

Jet Propagation and Mach Cones in (3+1)d Ideal Hydrodynamics

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Abstract. The observation of jet quenching and associated away-side Mach cone-like correlations at RHIC provide powerful “external” probes of the sQGP produced in A+A reactions [1], but it simultaneously raises the question where the jet energy was deposited. The nearly perfect bulk fluidity observed via elliptic flow suggests that Mach cone-like correlations may also be due to rapid local equilibration in the wake of penetrating jets. Multi-particle correlations lend further support to this possibility [2]. However, a combined study of energy deposition and fluid response is needed. We solve numerically 3-dimensional ideal hydrodynamical equations to compute the flow correlation patterns resulting from a variety of possible energy-momentum deposition models. Mach-cone correlations are shown to depend critically on the energy and momentum deposition mechanisms. They only survive for a special limited class of energy-momentum loss models, which assume significantly less longitudinal momentum loss than energy loss per unit length. We conclude that the correct interpretation of away-side jet correlations will require improved understanding and independent experimental constraints on the jet energy-momentum loss to fluid couplings.

1. Introduction

One of the major findings at the Relativistic Heavy Ion Collider (RHIC) is the suppression of highly energetic particles [1]. Two- and three-particle correlations of jet-associated intermediate- p_{\perp} particles provide an important test of the response of the medium to the details of the jet-quenching dynamics [2].

The observation of strong flow [3] suggests the possibility that the energy lost is quickly thermalized and incorporated in the local hydrodynamical flow. For a quantitative comparison to data a detailed model of both energy and momentum deposition coupled with a relativistic fluid model is needed [4, 5, 6].

We solve numerically (3 + 1)d ideal hydrodynamics [7], including a Bag Model Equation of State (EoS) with a critical temperature of 169 MeV to study the interactions

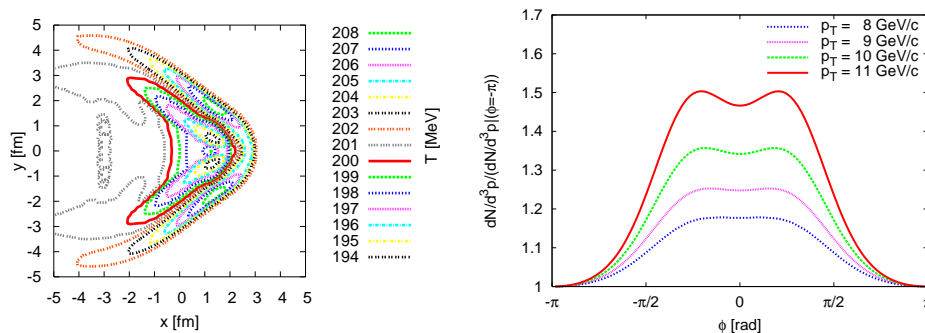


Figure 1. (Left panel) Temperature pattern after a hydrodynamical evolution of $t = 7.2$ fm/c, assuming a pure energy loss of $dE/dx = 1.4$ GeV/fm of a jet moving with $v_{\text{jet}} = 0.99c$ along the x -axis. (Right panel) Jet-signal strength determined after isochronous freeze-out for different p_{\perp} values.

of the jet with a medium for different energy- and momentum-deposition scenarios and to compute the flow-correlation patterns for the different energy-momentum-deposition models. Our focus is to study how hydrodynamical flow profiles (such as Mach cones), defined in configuration space, translate into momentum-space correlation functions via freeze-out. For this, we investigate the simplest situation of a uniform medium.

2. Jets in Ideal Hydrodynamics

In ideal hydrodynamics, the energy-momentum tensor is locally conserved. Adding a jet to the system, an extended set of equations including a source term S^{ν} has to be solved numerically,

$$\partial_{\mu} T^{\mu\nu} = S^{\nu} . \quad (1)$$

In this work, we will apply a source term

$$S^{\nu} = \int_{\tau_i}^{\tau_f} d\tau \frac{dP^{\nu}}{d\tau} \delta^{(4)}(x^{\mu} - x^{\mu}(\tau)) , \quad (2)$$

and assume a constant energy and momentum loss rate $dP^{\nu}/d\tau = (dE/d\tau, d\vec{M}/d\tau)$ along the trajectory of a jet $x^{\mu}(\tau) = x_0^{\mu} + u_{\text{jet}}^{\mu} \tau$, which moves with nearly the speed of light ($v_{\text{jet}} = 0.99c$) through a homogeneous, non-expanding background. We terminate the energy-momentum deposition of the jet after 5.6 fm/c of the hydrodynamical evolution. Additionally, we assume that the near-side jet contribution to the correlation function is not affected by the medium, although the observation of the ridge makes this assumption far from guaranteed.

Using the Cooper-Frye formula at midrapidity for pions, we perform an isochronous freeze-out after an evolution of $t = 7.2$ fm/c and determine the jet-signal strength by calculating the triple differential momentum distribution in jet direction (which is the direction of the away-side parton propagation) and normalizing to the distribution in direction opposite to the jet. Additionally, we determine the azimuthal two-particle correlations $1/N dN/d\phi dy|_{(y=0)}$ for the different deposition mechanisms.

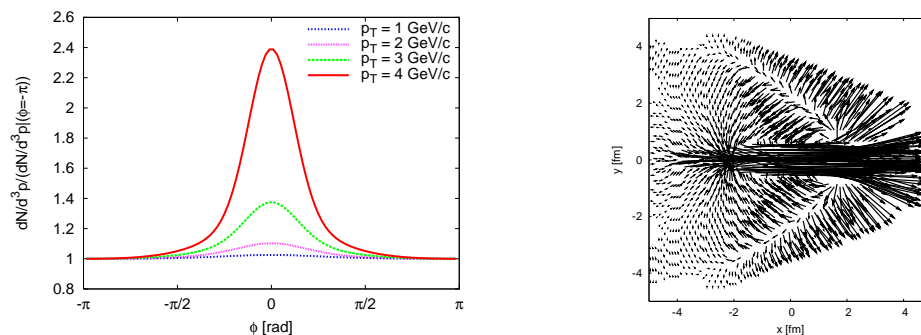


Figure 2. Jet-signal strength for different p_{\perp} values (left panel) and momentum distribution (right panel) after a hydrodynamical evolution of $t = 7.2$ fm/c, assuming a pure momentum deposition of $dM/dx = 1.4$ GeV/fm of a jet moving with $v_{\text{jet}} = 0.99c$ along the x -axis.

3. Jet-Deposition Mechanisms

In a first scenario, we study a source term which describes pure energy deposition, i.e., $dP^{\nu}/d\tau = (dE/d\tau, \vec{0})$ in Eq. (2), with $dE/dx = 1.4$ GeV/fm. The temperature pattern after $t = 7.2$ fm/c (see left panel of Fig. 1) reveals the formation of a cone-like structure. In the jet signal strength (see right panel of Fig. 1) this cone indeed appears in form of a double-peaked structure, but only if high p_{\perp} values are selected. This is due to the fact that thermal smearing washes out the signal for a high background temperature. Therefore, using p_{\perp} cuts similar to the experiment ($3 \leq p_{\perp} \leq 5$ GeV/fm), no cone-like structure emerges in the azimuthal two-particle correlations, but a broad away-side peak, if $dE/dx < 9$ GeV/fm. Of course, such away-side peaks will be produced in *any* jet-quenching mechanisms consistent with energy-momentum conservation, and hence its experimental observation is not enough to show that the jet energy has been locally thermalized. To do this, one might check if the height of the peak rises exponentially with the associated p_T .

As a second scenario, we investigate a source term with pure momentum deposition, i.e., $dP^{\nu}/d\tau = (0, d\vec{M}/d\tau)$ in Eq. (2), with $dM/dx = 1.4$ GeV/fm. This is justified since partons can be virtual. In this case, one peak occurs in jet direction (as can be seen from the left panel of Fig. 2), which is already visible for lower p_{\perp} values as compared to the first deposition scenario (cf. right panel of Fig. 1). The reason is that a diffusion wake is excited, which is indicated by the strong flow in jet direction (see right panel of Fig. 2).

The third scenario which we consider is characterized by a source term that describes a combined deposition of energy and momentum for a jet-energy loss of $dE/dx = 1.4$ GeV/fm and different ratios of the totally distributed momentum M_{jet} to the totally distributed energy E_{jet} . The cone-like shape only emerges for a small jet-momentum loss dM/dx and – due to the small value of the jet-energy loss dE/dx – for a high p_{\perp} value (see Fig. 3). For a larger jet-momentum loss, this structure is dissolved (caused by the creation of a diffusion wake) and a peak occurs in jet direction.

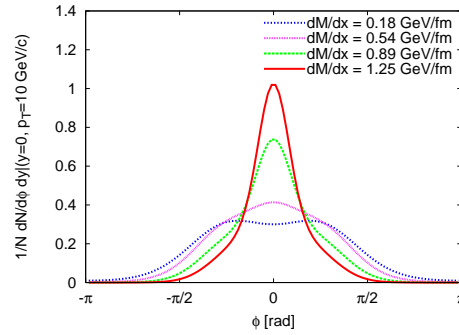


Figure 3. Azimuthal two-particle correlation, assuming a jet depositing both energy and momentum, for a jet-energy loss of $dE/dx = 1.4$ GeV/fm and different ratios of the totally distributed momentum M_{jet} to the totally distributed energy E_{jet} for a value of $p_{\perp} = 10$ GeV/c.

4. Summary

We found that the fluid response to a jet critically depends on the energy-momentum-deposition mechanism. A Mach cone-like pattern occurs in the azimuthal two-particle correlation only if the longitudinal jet-momentum loss is significantly less than the jet-energy loss ($dM/dx \ll dE/dx$), since otherwise the diffusion wake kills the Mach cone-like signal. This result is consistent with Refs. [4]. Moreover, applying p_{\perp} cuts similar to the experimentally used values ($3 \leq p_{\perp} \leq 5$ GeV/fm), a double-peaked conical signal does not emerge in the azimuthal two-particle correlation if $dE/dx < 9$ GeV/fm.

For a correct interpretation of the away-side jet correlations it is necessary to determine a realistic energy-momentum-deposition scenario in an expanding medium.

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